TDDB68 Concurrent Programming and Operating Systems

Lecture 2:
Introduction to C programming

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Outline

- Intro and basic principles in C
- Data types and variable definition/declaration
- Structures and arrays
- Pointers
- Storage classes and memory allocation
- Debugging
- Briefly about linking and loading

A bit of history

1965-1970

Multics

Unix

- More straightforward than Multics
- Early 1970's
- Originally implemented in assembly
- Needed a programming language

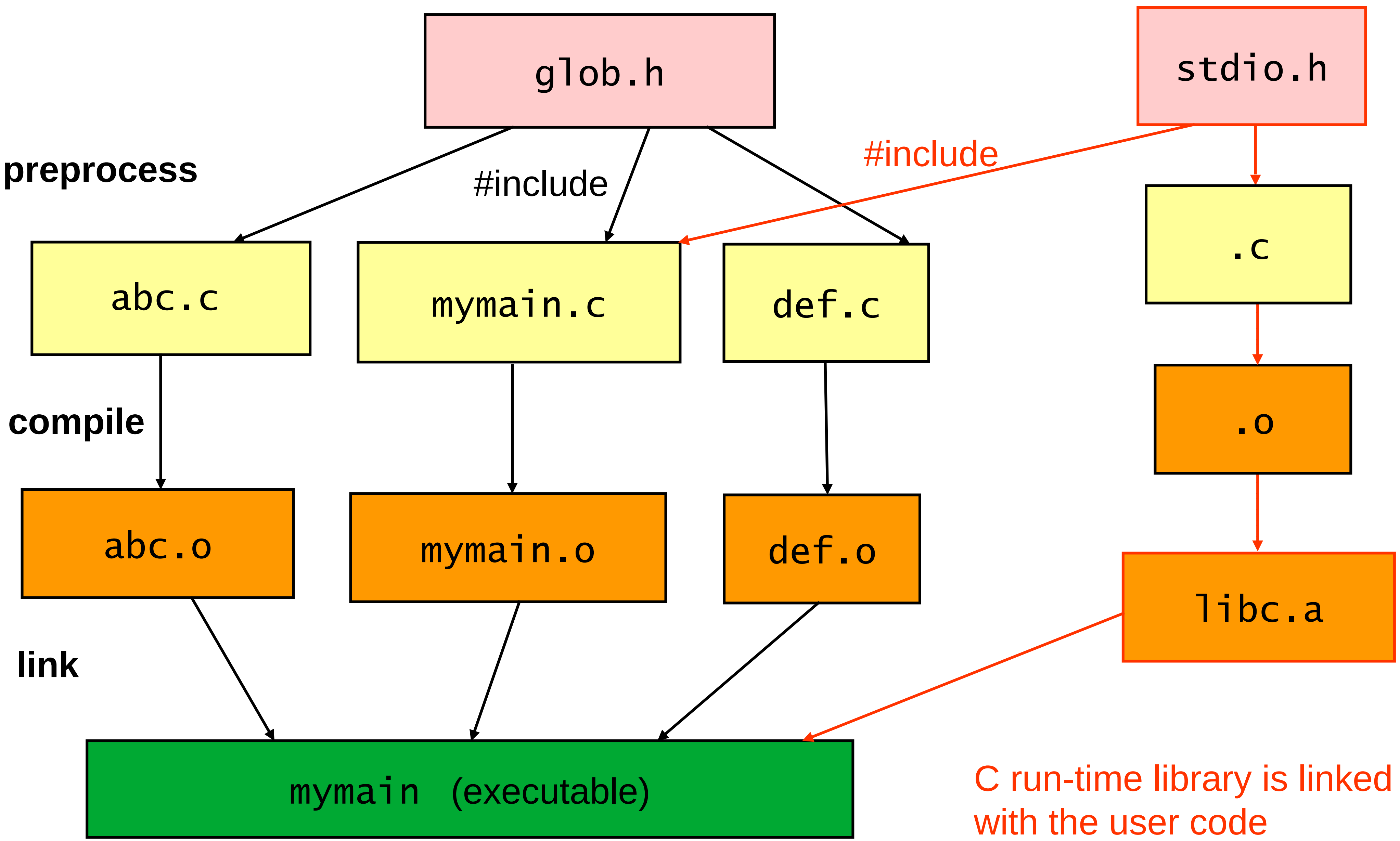
C programming language

- Successor of B, variant of BCPL
- Book 1978 by Brian W. Kernighan and Dennis M. Ritchie (”K&R-C”)
- 1989 ANSI standard
- Latest standard: C17

Basic principles

- Imperative
- Typed
- Medium abstraction level
- Structure
  - Flexible
  - Typically functionality-oriented

File relationships



A first program

Compiling C Programs

- Example: GNU C Compiler: gcc (Open Source)
- One command calls preprocessor, compiler, assembler, linker
- **Single module**: Compile and link (build executable):
  - gcc mymain.c   executable: a.out
  - gcc –o myprog mymain.c   rename executable
- **Multiple modules:** Compile and link separately
  - gcc –c –o mymain.o mymain.c   compiler only
  - gcc –c –o other.o other.c   compiles other.c
  - gcc other.o mymain.o   call the linker, -> a.out
- **make** (e.g. GNU gmake)
  - automates building process for several modules
- Check the man pages!

Data types in C

- **Primitive types**
  - int, char, etc.

- **Composite data types**
  - arrays
  - structures - struct
  - unions

- Programmer can define new type names with **typedef**

Primitive data types

- Integral types: **char**, **short**, **int**, **long, enum**
  - can be signed or unsigned, e.g. **unsigned int** counter;
  - sizes are implementation dependent (compiler/platform)
  - use **sizeof**(*datatype*) operator to write portable code
- Floating point types: **float**, **double**, **long double**
- Pointers

Constants and Enumerations

- **Constant variables:**

  const int red = 2;
  const int blue = 4;
  const int green = 5;
  const int yellow = 6;

- **Enumerations:**

  enum { red = 2, blue = 4, green, yellow } color;
  color = green;   // expanded by compiler to: color = 5;

- **With the preprocessor:**
  - symbolic names, textually expanded before compilation

    #define RED 2
    ...

No ”=” or ”;”

- In C, constants are often capitalized: RED, BLUE, ...

Variable declaration/definition

`glob.h`

```c
/* Comment: declaration of
   globally visible functions
   and variables: */
extern int incr( int );
extern int initval;
```

`abc.c`

```c
#include "glob.h"

// definition of var. initval:
int initval = 17;

// definition of func. incr:
int incr( int k )
{
  return k+1;
}
```

`mymain.c`

```c
#include <stdio.h>
#include "glob.h"

int counter;  // locally def.

void main( void )
{
  counter = initval;
  printf("new counter: %d",
          incr( counter ) );
}
```

Note the difference:
Declarations announce signatures (names+types).
Definitions declare (if not already done) AND allocate memory.
Header files should usually never contain definitions!

More on composite data types

Structures - struct

Unions

- Unions implement variant records
  - all attributes share the same storage
- Unions break type safety
- If handled with care, useful in low-level programming

Arrays

Array declaration/definition

int a[20];

int b[] = { 3, 6, 8, 4, 3 };

icplx c[4];

float matrix [3] [4];

Array addressing and access

- Addressing: ty a[size];
  Location of element a[i] starts at:
  (address of a) + i * elsize
  where elsize is the element size in bytes - `sizeof(ty)`

- Uses:
  a[3] = 1234567;
  a[21] = 345;   // ??, there is no array bound checking in C
  c[1].re = c[2].im;

- Arrays are just a different view of pointers

Pointer: type + address

The * symbol

- The * symbol has four **separate** uses:
  - Used for declaration/definition of a pointer:

    int *px;

    int **py;

  - Used to dereference a pointer (get the value the pointer is pointing to):

    *px = 5;

    int b = **py;

  - Multiplication:

    a = 3 * 4;
    a *= 4;

  - In comments:

    /* this is a comment */

The & symbol

- The & symbol has three **separate** uses:
  - Getting the address of a variable:

    int *p = &a;

  - Bitwise and:

    unsigned int x = y & z;
    y &= z;

  - Logical and:

    if (a && b) {
        ...

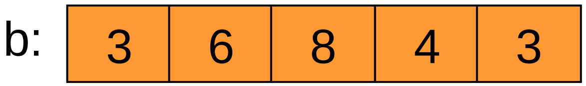
Pointer arithmetics

Pointer arithmetics

- Integral values can be added to / subtracted from pointers:

  ty *q = p + 7;
  // new value of q is (value of p) + 7 * sizeof(pointee-type of p: ty)

- Arrays are simply constant pointers to their first element:
  - Notation b[3] is ”syntactic sugar” for *(b + 3)
  - b[0] is the same as *b

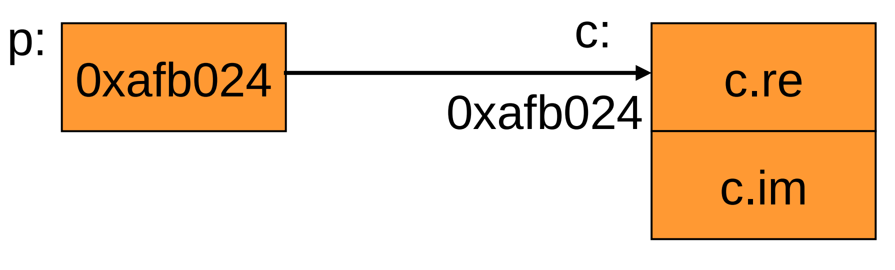


- A pointer can be subtracted from another pointer:
  - **unsigned int** offset = q – p;

Pointers and structs

- **struct** My_IComplex { **int** re; **int** im; } c, *p;
  p = &c;
  - p is a pointer to a struct

- p->re is shorthand for (*p).re
  - Example: as p points to c, &(p->re) is the same as &(c.re)
  - Example: elem->next = NULL;



Why do we need pointers in C?

- Defining recursive data structures (lists, trees, ...)

- Argument passing to functions
  - simulates reference parameters – missing in C (not C++)
    - **void** foo (**int** *p) { *p = 17; }   Call: foo (&i);

- Arrays are pointers
  - Handle to access dynamically allocated arrays
  - A 2D array is an array of pointers to arrays:
    - **int** m[3][4];   // m[2] is a pointer to start of third row of m

- For representing strings – missing in C as basic data type
  - **char** *s = "hello"; // s points to char-array {'h','e','l','l','o', 0 }

- For dirty hacks (low-level manipulation of data)

Pointer type casting

Pointer type casting

- Pointer types can be casted to other pointer types
  - **int** i = 1147114711;
    int *pi = &i;
    printf (”%f\n”, * ((**float** *) pi));   // prints 894.325623
  - All pointers have the same size (1 address word)
  - But no conversion of the pointed data!   (cf. unions)
    - Compare this to: printf(”%f\n”, (**float**) i);
  - A source of type unsafety,
    but often needed in low-level programming

- **Generic pointer type:**   **void** *
  - Pointee type is undefined
  - Always requires a pointer type cast before dereferencing

Pointers to functions (1)

- Function declaration
  - **int** f(**float**);

- Function call: f(x)
  - f is actually a (constant) pointer
    to the first instruction of function f in program memory
  - Call f(x)   dereferences pointer f
    - push argument x; save PC and other reg's; PC := f;

- Function pointer variable
  - **int** (*pf)(**float**);   // pf is a pointer to a function
    //   that takes a **float** and returns an **int**
  - pf = f;   // pf now contains start address of f
  - pf(x); // or (*pf)(x) dereferencing (call): same effect as f(x)

Pointers to functions (2)

- Most frequent use: generic functions and callbacks

- Example: Ordinary sort routine
  - ```
    void bubble_sort( int arr[], int asize )
    {  int i, j;
       for (i=0; I < asize-1; i++)
          for (j=i+1; j < asize; j++)
              if ( arr[i]   >   arr[j] )
                 ...  // interchange arr[i] and arr[j]
    }
    ```
  - Need to rewrite this for sorting in a different order?
  - Idea: Make bubble_sort generic in the compare function
    ```

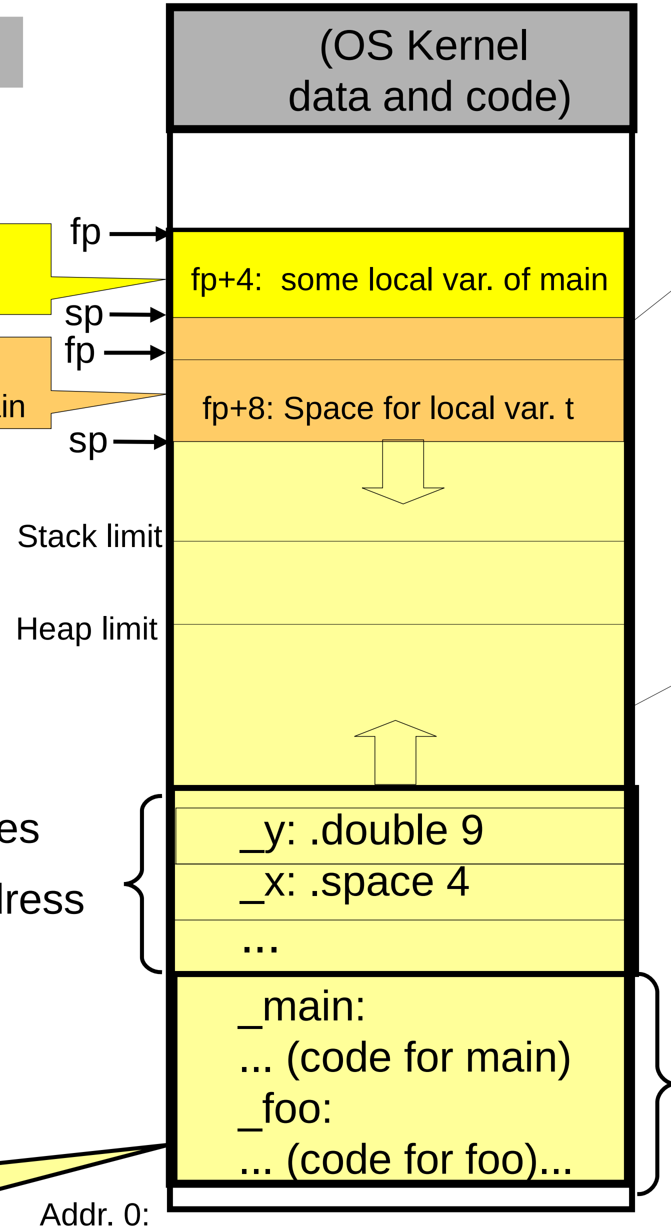
Pointers to functions (3)

- Most frequent use: generic functions and callbacks

- Example: Generic sort routine
  - ```
    void bubble_sort( int arr[], int asize, int (*cmp)(int,int) )
    { int i, j;
      for (i=0; I < asize-1; i++)
        for (j=i+1; j < asize; j++)
          if ( cmp ( arr[i] , arr[j] ) )
            ...  // interchange arr[i] and arr[j]
    }
    ```
  - `int gt ( int a, int b ) { if (a > b) return 1; else return 0; }`
  - ```
    bubble_sort ( somearray, 100, gt );
    bubble_sort ( otherarray, 200, lt );
    ```

Run-Time Memory Organization

NB: This is a simplification.



Stack

- Automatic variables
- allocated on the run-time stack at function call and removed on return
- indexed by frame pointer (or stack pointer)

Heap

- Dynamically allocated objects
- indexed via pointer variables

.data segment

- Global and static variables
- Indexed by absolute address (or globals pointer)

.text segment

- Compiled program code
- Copied in by loader
- branch target addresses: by absolute address or PC-relative

Storage classes in C

- **Automatic variables**

- **Global variables**

- **Static variables**

Automatic variables

- Local variables and formal parameters of a function
- Exist once per call
- Visible only within that function (and function call)
- Space allocated automatically on the function's stack frame
- Live only as long as the function executes

```
int *foo ( void )    // function returning a pointer to an int.
{
   int t = 3;     // local variable
   return &t;   // ??  t is (sort of) deallocated on return from foo,
   // so its address should not make sense to the caller...
}
```

Global variables

- Actually a misnomer, should be called extern storage class

- Declared and defined outside any function

  extern int y; // y seen from all modules; only declaration

  int y = 9; // only 1 definition of y for all modules seeing y

- Space allocated automatically when the program is loaded

Static variables

- **static int** counter;

- Allocated once for this module (i.e., not on the stack) even if declared within a function!

- Value will survive function return: next call sees it

Dynamic memory

Dynamic allocation of memory in C

- malloc(*N*)
  - allocates a block of *N* bytes on the heap
  - and returns a generic (**void** *) pointer to it;
  - this pointer can be *type-casted* to the expected pointer type
  - Example: icplx *p = (icplx *) malloc (**sizeof** (icplx));

- free(p)
  - deallocates the heap memory block pointed to by p

- Can be used e.g. for simulating ***dynamic arrays***:
  - Recall: arrays are pointers
  - **int** *a = (**int** *) malloc (k * **sizeof**(**int**)); a[3] = 17;

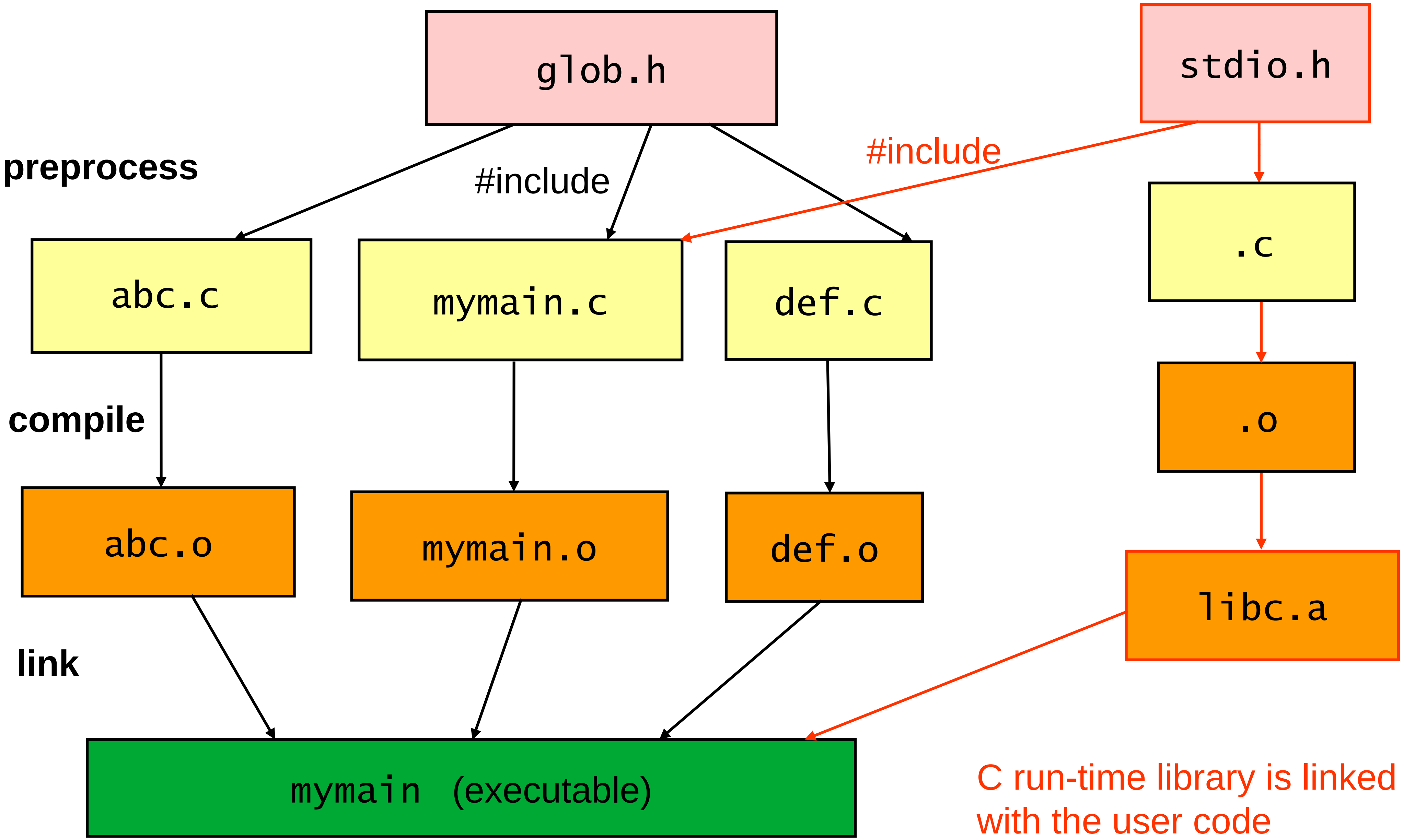
C: There is much more to say...

- Type conversions and casting
- Bit-level operations
- Operator precedence order
- Variadic functions
  (with a variable number of arguments, e.g. printf())
- C standard library
- C preprocessor macros
- I/O in C
- ...

Debugging

Linking and loading

File relationships



Lifetime of a program

- **Compiling:** source code → object code
- **Linking:** object code module(s) → executable
- **Loading:** executable on disk → program in main memory

How to relocate code?

Relocation table:
- line 3, patch base+1
- line 3, patch base+5

Symbolic addressing:

…

Definition of data X

…

If (X) goto P

…

P: …

as →

Relative addressing:

0: …

1: Space for data

2: …

3: If (*1) goto 5

4: …

5: …

loading →

Absolute addressing:

243: …

244: Space for data

245: …

246: If (*244) goto 248

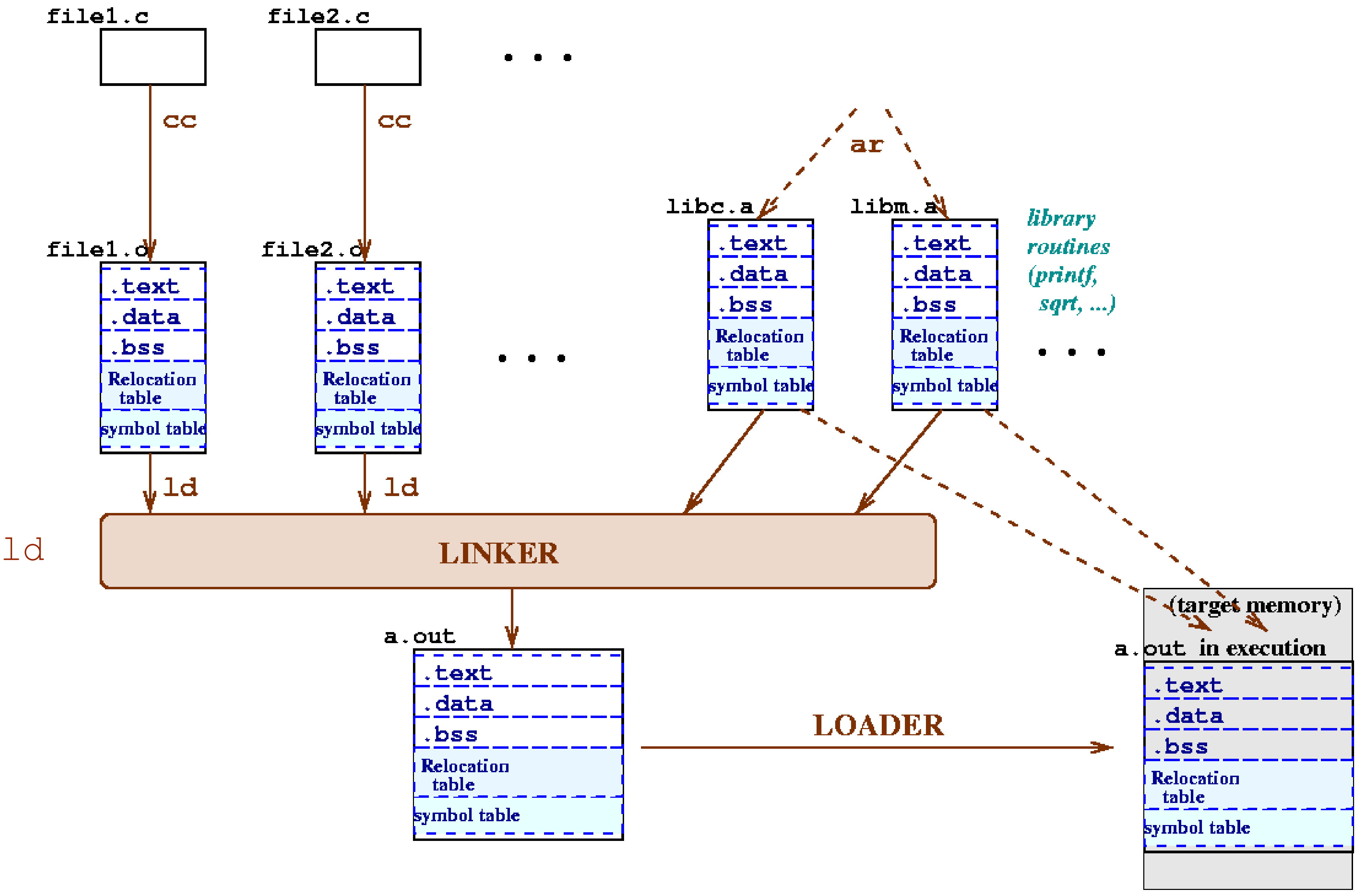
247: …

248: …

Linking Multiple Modules (1)

- Compiler (-c) created an **(object) module file** (.o, .bin)
  - Binary format, e.g. COFF (UNIX), ELF (Linux)
  - Non-executable (yet)
  - ***Segments*** for code, global data, stack / heap space
  - List of global symbols (e.g., functions, **extern** variables)
  - Addresses in each segment start at 0
  - ***Relocation table***:
    List of addresses/instructions that the linker must patch
    when changing the start address of the module
- ***Static relocation*** (at compile/link time):
  Merge all object modules to a single object module,
  with consecutive addresses in each segment type

Linking Multiple Modules (2)



Background: How the Linker Works

1) Read all object modules (including library archive modules)

2) Merge the code, data, stack/heap segments of these into a single code, data, stack/heap segment

3) Resolve global symbols (e.g., global functions, variables): check for duplicate globals, undefined globals

4) Write the resulting object module, with a new relocation table

5) Mark the resulting file executable.

Static vs dynamic

- Static linking: All modules are linked into one big executable
- Dynamic linking: Some modules are kept separate, and linked together at load time

- Static loading: All modules of a program are loaded into main memory
- Dynamic loading: Modules are loaded into memory on demand as they are needed

Next time

- Lecture 3: Processes, Threads, File Systems (I)
- Reading: Ch. 3.1-3.4, 4.1-4.3,4.5, 13.1 & 14.1-2